Prediction and physical analysis of unsteady flows around a pitching airfoil with the dynamic mesh approah in the context of fluid-structure interaction

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RÉSUMÉ. *L'interaction fluide-structure due au mouvement de tangage d'un profil d'aile NACA0012 a été étudiée à des nombres de Reynolds modérés et élevés. La méthode des maillages dynamiques a été employée au sein du code ICARE/IMFT pour la resolution des équations de Navier-Stokes de fluide compressible à nombre de Reynolds modéré. Les équations de Navier-Stokes en moyenne de phase fermées par des schémas URANS avancés pour la modélisation de la turbulence ont été résolues au sein du code NSMB pour des nombres de Reynolds élevés. La dynamique tourbillonnaire lors des phases de croissance et de décroissance de l'angle d'incidence et plus spécialement la dynamique du décrochage a été bien captée par la méthode des maillages dynamiques et par l'approche de macrosimulation URANS/Organised Eddy Simulation à nombre de Reynolds élevé.*

ABSTRACT. *The fluid-structure interaction due to the pitching motion of a NACA0012 aerofoil has been studied numerically at moderate and high Reynolds numbers. The dynamic mesh adaptation method has been employed in the code ICARE/IMFT solving the Navier-Stokes equations in compressible flows. At high Reynolds number, the phase-averaged Navier-Stokes equations have been solved, coupled with advanced URANS modelling in the NSMB code. The vortex dynamics due to the interaction and especially the stall are physically captured by the dynamic mesh adaptation method and by the URANS/Organised Eddy Simulation approach in low and high Reynolds numbers respectively.*

MOTS-CLÉS : *interaction fluide/structure, aile, tangage*

KEYWORDS: *fluid-structure interaction, airfoil, pitching*

1. Introduction

This work presents a numerical study and physical analysis of the flow around a NACA0012 pitching airfoil at moderate and high Reynolds numbers. The airfoil movement is an analytical rotation around the pitching axis. This kind of flow simulations allow studying the fluid-structure interaction in case of rigid lifting-bodies motion and to analyse physically different kinds of complex phenomena arising from the interaction, such as the buffeting (flapping shock waves) and the dynamic stall (sudden lift loss). Dramatic changes in the aerodynamic performance induced by this phenomenon are of significant interest for rotorcraft or highly maneuverable aircraft, for example. During the motion of the lifting structure, the flow detaches and reattaches over large parts of the body sueface. In the pitching case motion of high angle of attack, a highly energetic vortex structure is formed near the leading edge during the increasing angle phase. This structure is convected downstream, along the lifting surface and grows due to the adverse pressure gradient mechanism. During the ascending angle phase, the lift coefficient increases. The vortex structure is convected downstream in the wake, followed by the dynamic stall during the descending angle phase. These steps are characterised by a drastic decrease of lift and of the moment coefficients. A comprehensive review can by found in (McCroskey, 1982). Further experimental studies can be found in (Ahmed *et al.*, 1994; McAlister *et al.*, 1978; McCroskey *et al.*, 1976a; Carr *et al.*, 1977; Chandrasekhara *et al.*, 1990; Guo *et al.*, 1994). Numerical simulation of the dynamic stall can be found in (Metha, 1977; Choudhuri *et al.*, 1996; Guo *et al.*, 1994; Barakos *et al.*, 1999) at moderate Reynolds number range. Concerning the high Reynolds number range, the fully developed turbulent flow interacts non-linearly with the coherent vortex structures and yield a very complex dynamic physical process. The outcomes of the european research program UNSI, (Unsteady viscous methods in the context of fluid-structure interaction, 1998-2000)where the majority of the european aeronautical industries participated, addressed a comprehensive review of the URANS approaches to simulate the dynamic stall, Haase et al (2002). The major outcome was that the URANS approaches involving first-order turbulence modelling, including also non-linear behaviour laws, are not yet sufficient to accurately predict the dynamic stall phenomenon. The majority of these approaches used the Arbitrary Lagrangian Eulerian (ALE) approach to take into account the mesh movement.

In the present study an alternative is employed to take into account the domain and grid movement, the dynamic mesh adaptation approach, considered as more robust for capturing fast and drastic mesh deformation. This appraoch was studied by (Batina, 1990). In the present study, an analogy with a spring mesh canvas is used to update the grid, according to (Batina, 1990; Farhat *et al.*, 1998). In this paper, the governing equations of the flow are presented, as well as the methods of mesh motion. The performances of the dynamic mesh adaptation will be studied for a moderate-Reynolds number pitching motion, (Barakos *et al.*, 1999). Concerning the high-Reynolds number dynamic stall, an advanced URANS approach is employed, able to generate and to capture the stong vortex structures formation and detachment in non-linear interaction with the random turbulence background, the Organised Eddy Simulation, OES approach, (Braza, 2002), Braza et al (2006). The performances will be shown comparing to standard URANS concerning the pitching flow around a NACA0012 airfoil at high Reynolds number. The work carried out in the present paper consists of a first step towards the fluid-structure interaction (rigid motion). In our studies in progress, the deformation of the structure in the interaction will be taken into account.

2. Numerical method

2.1. *Navier-Stokes equations discretisation scheme*

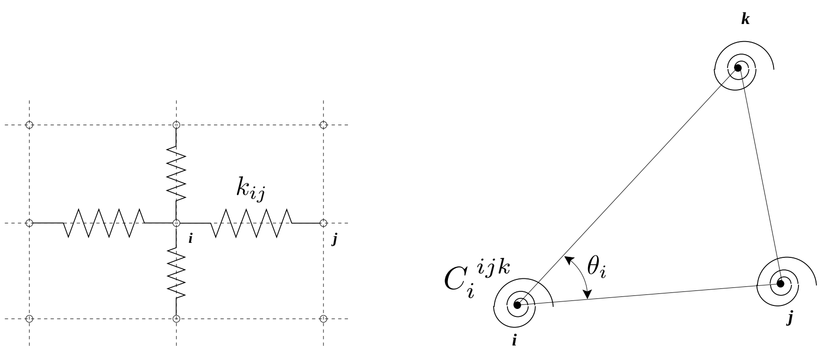
The complete time-dependent Navier-Stokes equations have been solved in three dimensions under a conservative form, in a general non-orthogonal curvilinear coordinates system. The Roe upwind scheme (Roe, 1981) has been used to discretise the convection and pressure terms because of their hyperbolic character. The MUSCL approach by van Leer (Leer, 1979) has been employed in order to increase the spatial accuracy from the first to second order. This scheme provide good accuracy and stability as studied in detail by (Bouhadji *et al.*, 2003a). This scheme has been used without limiter. A careful grid refinement has been performed to avoid any spurious wiggle oscillation. However, in the higher Reynolds number ranges, the use of limiters is recommendable to ensure monotonicity with the use of reasonable grid sizes. The diffusion terms have been discretised by central differences and the temporal terms using an explicit, third order of precision in time, three-stage Runge-Kutta TVD scheme (Shu *et al.*, 1988). The computational domain is a C-Type grid, many grid size had been used, 201×59, 369×89

and 501×101 nodes in order to provide grid-independent solutions. A distance of ten chord-lengths separates the leading edge from the outflow boundary and there are seven chordlengths between the airfoil and the outer boundary.

Freestream conditions have been imposed at the outer boundaries, except for the downstream one, where a first order extrapolation has been used. On the airfoil surface Neumann conditions are used for the temperature (adiabatic wall), density and energy. Pressure has been computed from the momentum equation which was solved numerically with adherent condition for the velocities. Along the wake line, the boundary values of the velocity, pressure and density have been computed by averaging the mentioned variables from adjacent lines above and below the wake line. Detailed numerical tests have been carried out (Bouhadji, 1998) to ensure that the boundary conditions and the computational domain size do not produce any spurious effect. The numerical characteristics of the present solver $ICARE$ for compressible flows and its behaviour in respect of the boundary conditions have been reported in detail by (Bouhadji *et al.*, 2003b), (Bouhadji *et al.*, 2003a),(Bouhadji *et al.*, 1997), (Bouhadji *et al.*, 1998). We have ensured that the outer boundary was positioned far enough from the airfoil to match with simulations that used non-reflecting boundary conditions (Blaschak *et al.*, 1988), (Jin *et al.*, 1993).

2.2. *Moving domain equations*

The grid is moving to follow the pitching motion of the solid walls. It is therefore necessary to take into account the velocities of the grid nodes. This is the principle of the dynamic mesh adaptation, achieved by taking into account in the Navier-Stokes equations two referential systems, the Eulerian and mixte coordinates, (Bourdet, 2005; Lefrançois, 1998). The convective fluxes are written in relative velocities taking into account the nodes motion. The first step is to solve the new system of equations. The second step is the updating of the ensemble of metric parameters induced by the grid. To achieve this, it is necessary to update the grid along each new aerofoil position. This is performed by employing a spring mesh canvas analogy : the springs of tension-compression, (Batina, 1990) as well as the torsion springs, (Farhat *et al.*, 1998) (Fig 1).



(a) Tension-compression springs (b) Ressorts de torsion

Figure 1. *Springs analogy for grid updating.*

The tension-compression springs are ficticious springs that are attached in each segment that links two adjacent grid nodes, (Fig 1(a)). The spring stiffness, k_{ij}, is chosen inversely proprtional to the distance between the nodes, l_{ij} of the considered segment :

$$k_{ij} = \frac{1}{l_{ij}} \quad \text{where} \quad l_{ij} = \phi[(x_i - x_j)^2 + (y_i - y_j)^2]^{\alpha},$$

where ϕ and α are adaptative parameters.

Concerning the torsion springs, the principle is aquivalent : in each edge, i, j et k of a triedron formed by three adjacent grid nodes a torsion spring is associated to a stiffness defined by angular considerations.

For a node i, we define θ_i as the angle between the two segments ij and ik (Fig 1(b)). On each grid point, a torsion spring is attached for each triangle connected to this point. The torsion spring stiffness is C_i^{ijk}, definied by :

$$C_i^{ijk} = \frac{1}{\sin^2 \theta_i} \ .$$

The first spring type allows avoiding the coincidence between two grid points, because the stiffness increases as the points are approaching each other. The second spring type allows avoiding the passage of grid lines in between the segment.

After each new aerofoil position, the new position of the grid points is defined by solving iteratively the static equilibrium equation of the spring grid canvas. Therefore, the displacement and the velocity of the nodes are determined, as well as the updating of the metrics needed for the Navier-Stokes system solution.

The grid motion can produce in some cases mass sources or sinks. This may contribute to appearance of numerical oscillations. To avoid this, an additional conservation equation has to be solved, the *geometrical conservation law*, (Thomas *et al.*, 1979; Bourdet, 2005). This law is derived from the fact that the temporal variation of a volume of fluid, whose velocity surface field is $\mathbf{W}_s$, has to be equal to the volumes sweeped by the domain oriented surfaces. This law can be written in an analogy to the mass conservation law, as follows :

$$\frac{d}{dt} \int_{\mathcal{V}} d\mathcal{V} = \int_{S} \mathbf{W}_s . d\mathbf{S} \ ,$$

where $\mathcal{V}$ is the volume of the domain considered and S its surface. This equation has been implemented in the whole numerical code $ICARE$ of our team, (Bouhadji, 1998). Detailed tests have been carried out to ensure that the results are not affected by numerical perturbations due to the grid movement, (Bourdet, 2005).

3. Flow configuration

The flow configuration to be examined is the pitching NACA0012 airfoil at $Re_\infty = 5000$, Mach number $M_\infty = 0.4$. The pitching motion is imposed around an axis at 0.25 chord length from the leading edge, (Fig 2), according to the oscillation law :

$$\alpha(t) = \alpha_0 + \Delta\alpha \ \sin(\omega t)$$

where α_0 is the mean angle of attack, $\Delta\alpha$ is the oscillation amplitude beyond the mean and ω the pulsation. The reduced frequency $k = {}^{\omega c}/_{2U_\infty}$ of the aerofoil's motion is $k = 0.25$. The above test case had been studied numerically by (Barakos *et al.*, 1999), using ALE.

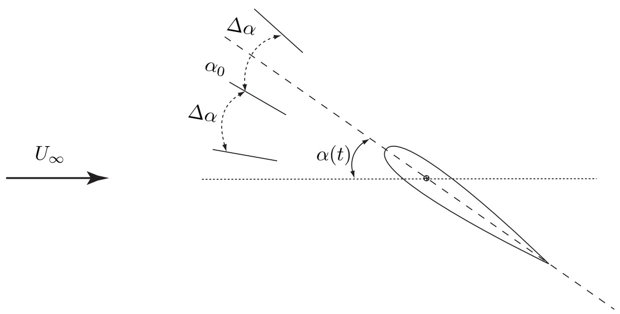
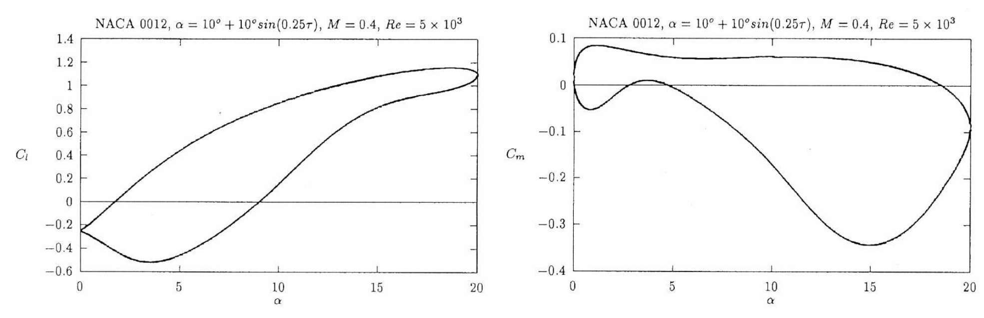


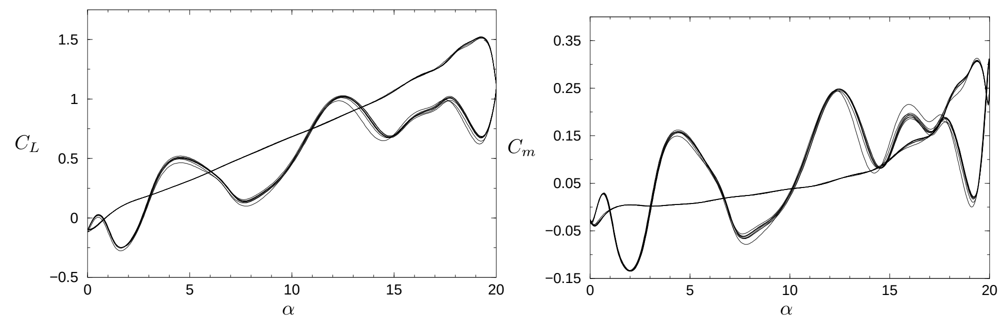
Figure 2. *Schematic representation of the pitching airfoil oscillations.*

3.1. *Results*

In figure 3, a comparison of the results by the present study and by the previous one (Barakos *et al.*, 1999), is shown, concerning the lift and moment coefficients.



(a) Results of Barakos et al, (1999)



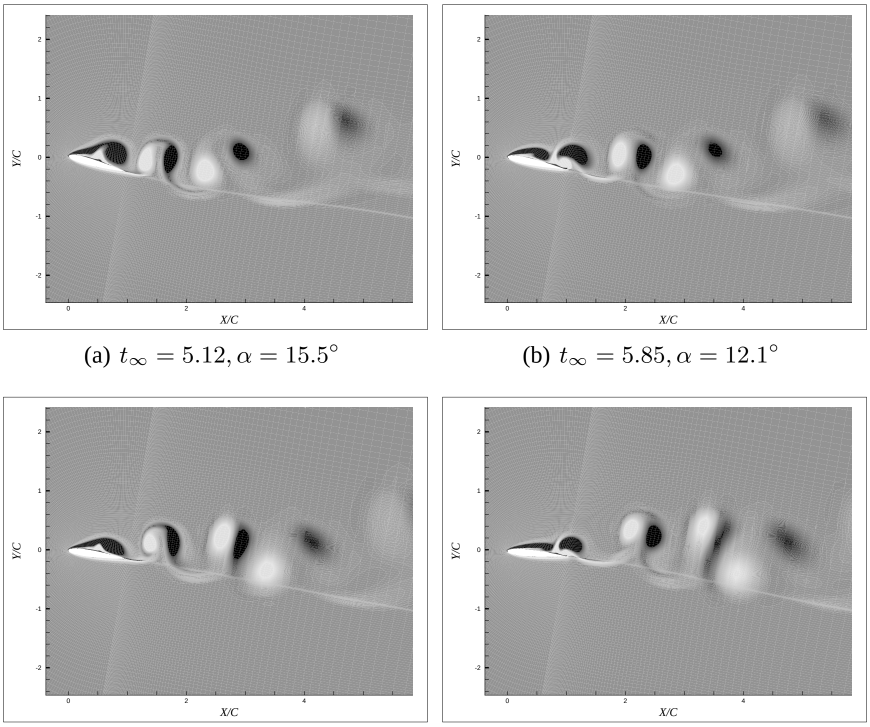
(b) Results of the present study

Figure 3. *Evolution of the lift and moment coefficients,* $Re_\infty = 5000$, $M_\infty = 0.4$, $k = 0.25$.

The amplitudes of the lift and moment coefficients simulated by the present study are qualitatively coherent with the resultats by (Barakos *et al.*, 1999). However, there are significant diffrences concerning the dynamic stall vortices :

The first difference indicates a drastically different behavior on the kind of dynamic stall. Both studies show a strong hysteresis character during the oscillation cycle, (Fig 3(a)). The stall occurs at the maximum incidence in the study by (Barakos *et al.*, 1999), whereas it appears at about $19.3°$ in the present study, before the maximum angle is reached.

The second difference is the formation of a number of secondary peaks in the present study along the suction side, concerning the lift and drag coefficients, (Fig 3(b)). These peaks correspond to the passage of smaller scale organised eddies along the suction side. Indeed, the vortex dynamics quantified by the present study are more complex than the previous study, where only one vortex structure is convected and creates the dynamic stall. In figures (Fig 4), the vorticity iso-contours are presented at four instantaneous snapshots, allowing tracking of the vortex structures during the flow motion. These structures are not organised along a von-Kármán vortex street, but according to a jet like structure, forming the well known mushroom patterns that characterise the pitching motions, (Chandrasekhara *et al.*, 1990), (Choudhuri *et al.*, 1996). The existence of a multitude of vortices beyond the von-Kármán ones in moderate Reynolds number range ($Re > 2000$) is also a fact reported by incompressible flow studies around the NACA0012 wing,Hoarau et al, (2003).



(a) $t_\infty = 5.12, \alpha = 15.5°$

(b) $t_\infty = 5.85, \alpha = 12.1°$

(c) $t_\infty = 6.6, \alpha = 8.5°$

(d) $t_\infty = 7.3, \alpha = 5°$

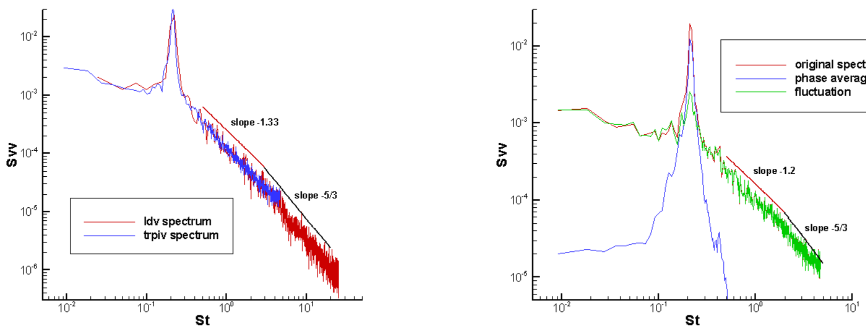
Figure 4. *Vorticity iso-contours - descendant phase of the pitching motion,* $Re_\infty = 5000$, $M_\infty = 0.4$, $k = 0.25$, *in white the positive vorticity, in black the negative vorticity.*

4. High-Reynolds number pitching motion of the NACA0012 airfoil

In this section, the high-Reynolds number flow around a NACA0012 airfoil is investigated by using appropriate URANS modelling. This is achieved by means of the Organised Eddy Simulation, OES approach.

4.1. *The Organised Eddy Simulation approach*

In the context of the URANS/OES macrosimulation (Organised Eddy Simulation), (Dervieux et al (1998), Braza et al (2006)), the turbulent spectrum is decomposed in a first part regrouping all the coherent processes (*resolved part)* and in a second part regrouping all the chaotic processes *independently on their size (spectrum to be modelled),* as presented schematically in fig. 6. It is recalled that in LES the distinction is done according to the structures size and this limitates this approach to moderate Re-numbers concerning wall-turbulence around bodies. The fact that the spectrum part to be modelled in OES is extended from the low to the high frequencies allows the use of statistical turbulence modelling, that is very efficient in high Reynolds number modelling of wall flows. In the time-domain, the equations are the phase-averaged Navier-Stokes equations, where the turbulent stresses have to be modelled by reconsidered statistical turbulence modelling closures. We had conjectured ((Braza, 2002)) that due to the non-linear interaction between the coherent part and the incoherent one, *there must exist a shape and slope modification* of the inertial part in the spectrum, in the vicinity of the peak. This has been now quantified, either by means of the LDV data or by the present study (time-dependent PIV data), (Braza *et al.*, 2006) . The modification of the energy spectrum in the inertial range leads to modified turbulence scales in the context of the statistical two-equation modelling, as achieved in a previous work of us, (Jin *et al.*, 1994), (Hoarau *et al.*, 2002), (Bouhadji *et al.*, 2002), Bourguet et al (2006), by means of the second-order moment closures. This yields a reconsideration of



a) b)

Figure 5. *Turbulence spectra in the detached flow past a cylinder at Re=140000,(x/D=1 y/D=0.375), (Braza et al, 2006), showing the slope modification in the inertial range due to interaction between the coherent structures and random turbulence ; a) LDV (Djeridi et al (2003) and PIV turbulence spectra ; b) Time-resolved PIV spectrum*

the eddy-diffusion coefficient for the class of two-equation modelling, as well as an improved damping function to attenuate turbulence towards the wall, (Jin *et al.*, 1994).

4.2. *Results*

Computations are performed with the NSMB code (Navier-Stokes multiblock) for the test-case of ((McCroskey *et al.*, 1976a)), ((McCroskey *et al.*, 1976b)) and ((McAlister *et al.*, 1978)) at Reynolds number of order one million. The computations have been carried out by means of a fully parallel (MPI) version of the code on the IBM Power 4 and on Silicon Graphics Origin 3000 supercomputers, using an order of 16 parallel processors for the present 2D study. The physical parameters of the simulation are given in in fig. 7. An O-type mesh has been used. The modified OES k-epsilon, and OES-k-omega turbulence models, ((Hoarau *et al.*, 2002)) are compared with the behaviour of the k-omega/SST model ((Menter, 1994)). The computational grid is 500 x 226. The unsteady global parameters versus time are shown in fig. 8 and in fig. 9. A good comparison with the experimental data by Mc Croskey and Mc Alistair is achieved. Table 10 shows the maxima and minima of the averaged aerodynamic coefficients in comparison with the experiment. The iso-vorticity contours are shown in figures 11 and fig. 12 according to the OES-k-epsilon and k-omega/SST respectively. The OES-k-epsilon allows a more rich creation of organised vortices that are inhibited by the k-omega-SST, especially in the descending phase of the motion. The OES-k-omega provides practically comparable results with the OES-k-espilon model in respect of the iso-vorticity contour dynamics and for the sake of saving space, these results are not presented. The overall comparison between the OES approach and previous URANS one (the SST in this case) indicates the improvements achieved by OES using the same grid size.

The fluid-structure interaction according to the present study captured by the OES approach yields the formation of a series of smallers-scale organised vortices downstream of the leading edge during the ascending phases of the motion, (angles $14.1°$ and $17.2°$, fig. 11). These vortices considerably grow and detach practically from the leading edge during the descending phase of the motion. The convected vortex downstream of the trailing edge forms a mushroom like structure, (angle $24.2°$).

5. Conclusion

The dynamic mesh adaptation method indicates a robust behavior and provides results that capture the fluid-structure interaction dynamics in the case of pitching airfoils motion, providing rich vortex dynamics in accordance with experimental visualisations. The numerical approach by this method indicates achievement of more accurate

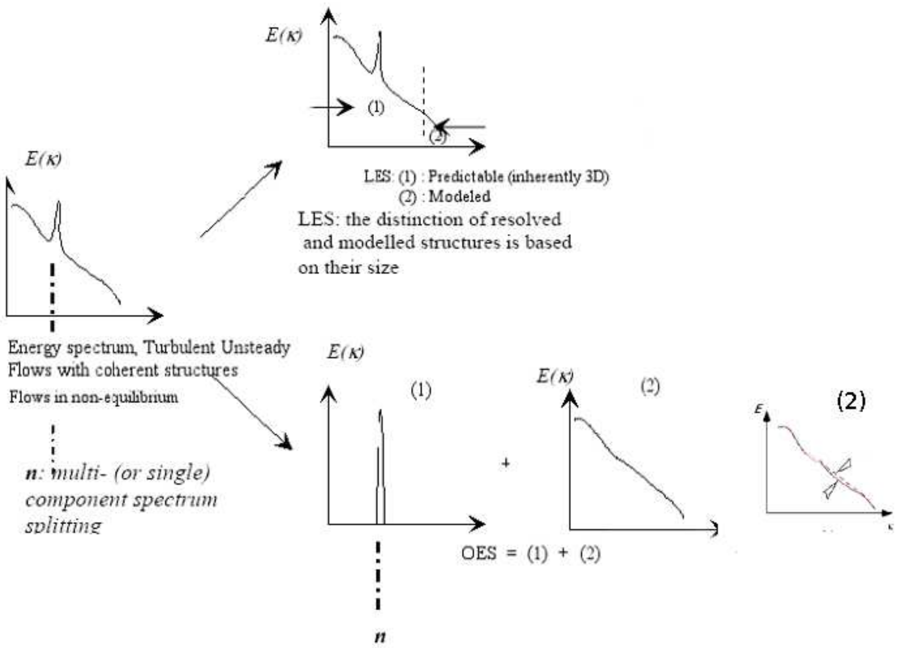


Figure 6. *Schematic representation of the energy spectrum in the URANS/Organised Eddy Simulation approach : the distinction between the structures to be resolved and those to be modelled is based upon their organised or random character. Part (2) of the non-equilibrium energy spectrum modelled by reconsidered, advanced statistical turbulence modelling, due to the inertial-range specrum modulation, schematically shown on the right.*

Reynolds number	0.98×10^6
Mean incidence	15°
Oscillation amplitude ($\Delta\alpha$)	10°
Pitch axis location	¼ of chord length
Oscillation frequency (ω)	0.0170383 rad/sec
Reduced frequency	0.1
Mach Number	0.072

Figure 7. *Table 1. Physical flow parameters*

dynamic stall phenomenon in respect to the physics. The OES macrosimulation approach provides a good representation of the vortex dynamics concerning the interaction at high Reynolds number turbulent pitching flow around the NACA0012 airfoil, with extrema aerodynamic parameters close to the experiment. This approach provides a more rich coherent structures dynamics in the formation and the stall phases than previous URANS approaches.

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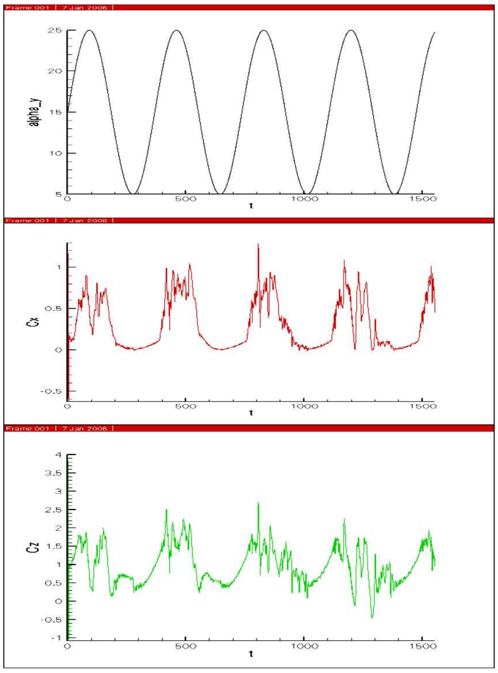

Figure 8. *Time-dependent aerodynamic coefficients (drag, lift), k-epsilon-OES*

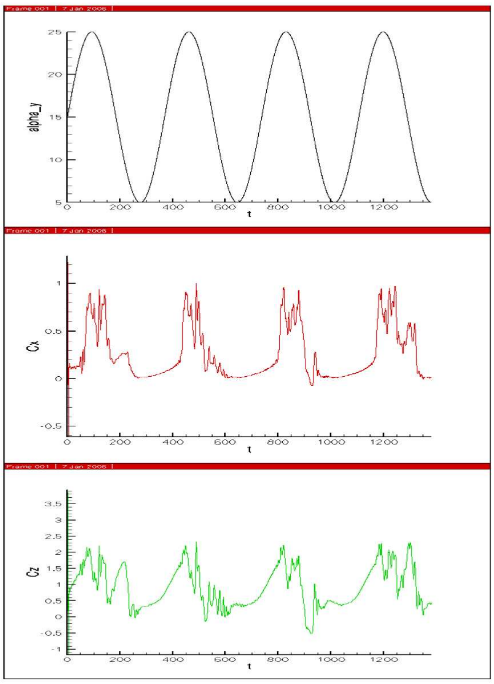

Figure 9. *Time-dependent aerodynamic coefficients (drag, lift), k-omega-SST*

	Experiment	OES/k-ω	OES/k-ε	k-ω/SST
C_D(max)	0.92	0.9	0.9	0.9
C_L(max)	2.2	2.1	2.1	2.0
C_m(min)	-0.4	-0.36	-0.36	-0.3

Figure 10. *Averaged maximum values of the aerodynamic coefficients*

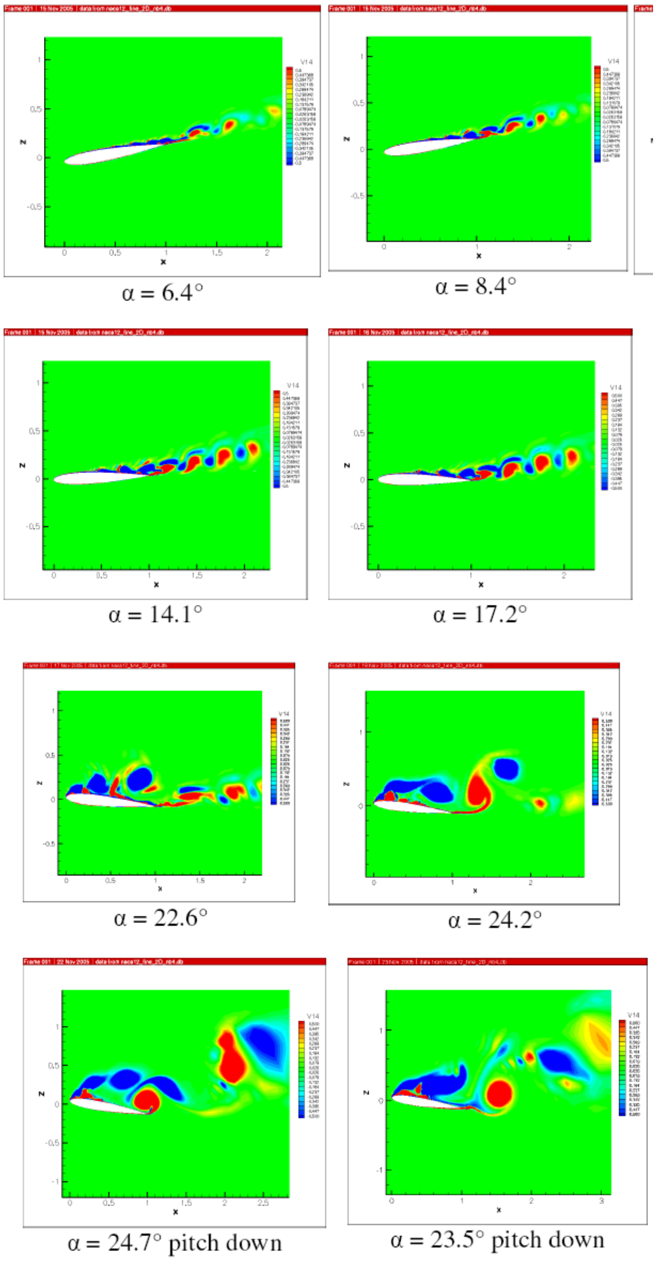

Figure 11. *Iso-vorticity contours at different phase angles, k-epsilon-OES*

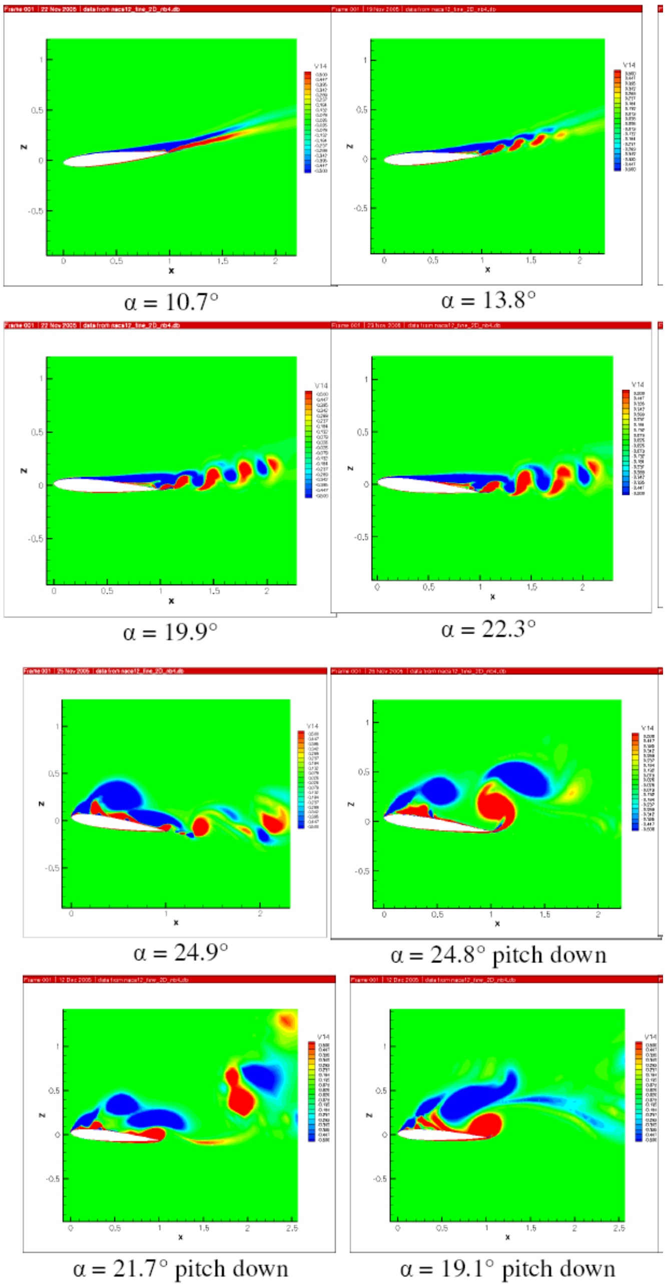

Figure 12. *Iso-vorticity contours at different phase angles, k-omega-SST*

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